SECTION IV

TIME AND FREQUENCY TRANSFER

In this section we discuss several methods available for transferring time and frequency from one location to another. Transfer of time is usually referred to as "time synchronization" whereas frequency transfer is termed "calibration". Since synchronization normally implies that calibration is also accomplished, for this discussion the term synchronization is intended to include both time synchronization and frequency calibration.

As was mentioned in Section I, synchronization can be either relative or absolute. In absolute synchronization, the user or operator of a clock or clocks references them to the internationally defined frequency as well as UTC. This requires that the clock is traceable to a national laboratory which contributes to the internationally Coordinated Universal Time (UTC) scale. AN 52-1, Fundamentals of Time and Frequency Standards, contains a listing of national laboratories around the world.

In relative synchronization, the user has several clocks or standards which must be kept close to each other in frequency or time, but have no concern with absolute time reference because there is no need to interface with clocks or standards outside his system.

We can also refer to "real" synchronization or "paper" synchronization. "Real" synchronization refers to the situation where the local clock is actually adjusted to the correct frequency and time. "Paper" synchronization refers to measuring the differences in frequency and time between local and reference clocks but no adjustments are made. "Real" synchronization is normally performed in systems using quartz or rubidium standards because of their characteristic frequency drift. "Real" synchronization can also be performed with cesium standards; however, "paper" synchronization is more common in order to preclude human error that sometimes occurs whenever operator intervention is allowed. The lack of frequency-drift in cesium frequency standards makes this convenient.

The criteria for selecting either "real" or "paper" synchronization is the maximum amount of error in either time or frequency which is tolerable in the system. The larger the error-tolerance, the less often "real" synchronization need be performed. Interim measurements may be made between adjustments to provide additional confidence in the system and insure that nothing catastrophic has occurred in the meantime. Obviously, the frequency of interim measurements and periodic "real" synchronization is dependent upon the error-tolerances, accuracy and drifts in the system, costs of measurements and synchronization, and the level of confidence the user requires in the system operation.

Several popular methods for accomplishing time synchronization and frequency calibration are contained in the following paragraphs.

COMPARISON OF VARIOUS TIME AND FREQUENCY TRANSFER TECHNIQUES

Table 4-1 is useful in comparing the salient characteristics of several time and frequency transfer techniques. The table is intended to show the relative merits of each technique and is not intended to provide absolute limits on their performance. Additional information on each technique is contained in the sections that follow, as well as the references listed in the bibliography.

Table 4-1. Comparison of selected time/frequency transfer techniques.
Courtesy of National Bureau of Standards (NBS Monograph 140, p.301)

TRANSFER TECHNIQUES		STATUS (1)	ACCURACY-FREQUENCY SYNCHRONIZATION	ACCURACY FOR DATE TRANSFER	AMBIGUITY (4)	COVERAGE FOR STATED ACCURACY	% OF TIME AVAILABLE	RELIABILITY	RECEIVER COST FOR STATED ACCURACY	COST PER CALIBRATION	NUMBER OF USERS THAT CAN BE SERVED	OPERATOR SKILL REQUIRED FOR STATED ACCURACY
VLF RADIO	COMMUNICATION/SFB GBR, NBA, WWVL	O	1×10^{-11} (3)	ENVELOPE 500 μs	/ PHASE ~50 μs	GLOBAL						
	NAVIGATION SYSTEM OMEGA	O/P	$<1\times10^{-11}$ (3)	≤ 10 μs■	PROPOSED CODE- 1 YR / PHASE ~100 μs	GLOBAL			MODERATE			TIME CODE
LF RADIO	STANDARD FREQ. BROADCAST (WWVB)	O	1×10^{-11} (PHASE-24h) (3)	ENVELOPE ~1 ms	1 YR /	USA (WWVB) LIMITED			MODERATE		USA (WWVB) EUROPE OTHERS	
	NAVIGATION SYSTEM LORAN-C	O	1×10^{-12} GND (3)	~1 μs(GND) 50 μs(SKY)	50ms / PHASE 10 μs	SPECIAL ◆ AREAS					SPECIAL AREAS	
HF/MF RADIO	STANDARD FREQ. BROADCASTS (WWV)	O	1×10^{7}	1000 μs	1 DAY / 0.5 min	HEMISPHERE		DEPENDS ON CONDITIONS				
	NAVIGATION SYSTEM LORAN-A	O	5×10^{11} (2)	2-5 μs NOT UTC		LIMITED AREAS		DEPENDS ON CONDITIONS			SPECIAL AREAS	
TELEVISION (VHF/SHF RADIO)	PASSIVE -LINE- 10	O	1×10^{-11} (24h)	~1 μs	1 DAY / ~33ms	NETWORK COVERAGE	"LIVE" PROGRAMS				USA FOR EXAMPLE	
	ACTIVE-LINE-1 (NBS TV TIME SYSTEM)	E	1×10^{-11} (< 30 min)	<100ns ▲	1 DAY / ~33ms	NETWORK COVERAGE					USA FOR EXAMPLE	
SATELLITES (VHF/UHF/SHF RADIO)	STATIONARY SATELLITES (TRANSPONDER) ONE WAY	E/O	1×10^{-10} (24h)	10-50 μs	DEPENDS ON FORMAT	HEMISPHERE	STATIONARY					
	STATIONARY SATELLITES (TRANSPONDER) TWO WAY	E/O	1×10^{-12} (24h)	~100ns	DEPENDS ON FORMAT	HEMISPHERE			MODERATE			
	ON-BOARD CLOCK (ACTIVE) ONE WAY - LOW ALTITUDE	O	$\sim1\times10^{-10}$ (24h)	0.5-50 μs	DEPENDS ON FORMAT	WORLD	10-15 min PER PASS 2-4 PER DAY	CLOCK NEEDS ADJUSTMENT				
SHF RADIO	MICROWAVE	E/O	$\sim1\times10^{-13}$ (PER WEEK)	≤100ns	PHASE COMPARISON	LOCAL LINKS						
	VLBI	P	5×10^{-14}	~1ns	DEPENDS ON FORMAT	HEMISPHERE	AS NEEDED					
PORTABLE CLOCKS	PHYSICAL TRANSFER	O	1×10^{12}	100ns●	1 DAY	LIMITED BY TRANSPORTATION	AS NEEDED		NONE			
	AIRCRAFT FLYOVER 2-WAY	E	1×10^{12}	≤100ns	DEPENDS ON FORMAT	LIMITED BY TRANSPORTATION	AS NEEDED					
PULSARS	OPTICAL SIGNAL→ NP 0532	P	1×10^{10}	~10 μs	~33ms	HEMISPHERE	NIGHTTIME					
AC POWER LINE	POWER NETWORK SYSTEM	P	1×10^{8}	~1ms	16.7ms	CONTINENTAL USA			MINIMAL	MINIMAL	CONTINENTAL USA	

GOOD FAIR POOR

NOTES: (1) Status of technique indicated as follows: O–Operational; P–Proposed; E/O–Experimental operational. (2) Estimates of day-to-day measurements within 2000 km(1250 mi) of Loran-A stations. These emissions not coordinated with UTC and manually operated crystal clocks drift. (3) From day-to-day phase measurements e.g., 1 μs per day phase change approximates 1 pt. in 10^{11} in frequency difference. (4) Left-hand designation gives the shortest time interval that cannot be resolved; Right-hand number gives basic ambiguity. ◆, by ground wave 1600 km; by sky wave thousands of kilometers depending upon conditions. ■, with proposed time code. ●, closure after 1 day. ▲, within local service area of TV transmitter and path delay known.

Here is a further amplification on some of the characteristics listed in the table. ACCURACY OF FREQUENCY SYNCHRONIZATION refers to the uncertainties inherent in the medium which limit the accuracy to which frequency standards can be synchronized or calibrated.

ACCURACY FOR DATE TRANSFER is the accuracy to which time-of-day can be transferred or synchronized at a given location. The values given are average values and must be adjusted for either extremely favorable or unfavorable conditions.

AMBIGUITY is the coarsest time interval a time-transfer can provide directly with certainty. For example, an ordinary wall clock has an ambiguity of 12 hours. One must know by other means the year, month, day, and whether it is AM or PM, the clock does the rest.

The qualitative ratings of good, fair and poor in the chart are given for purposes of comparison and evaluation and as such are arbitrary and broad.

HIGH FREQUENCY TRANSMISSIONS

General characteristics of high frequency and low frequency propagation were discussed in AN 52-1 where it was pointed out that high frequency signal propagation is subject to erratic variations, particularly, phase delays. These and other problems can usually be eliminated by the use of LF ground wave and satellite signals.

An AM receiver, tunable to the needed frequencies (for WWV: 5, 10, and 15 MHz) is the basic requirement. The receiver's capability and complexity (hence cost) depends upon the degree of precision demanded of the measurement and upon the received signal strength at the user's location.

Accuracy. Generally, frequency transfers within the groundwave of HF transmissions (~160 km) can be made with the same accuracy as the transmitted signal. However, at distances using skywave paths, the accuracy is limited to 1×10^{-7} for frequency transfer and 1 ms for time transfer. Measurements over long periods of time can result in better accuracy using averaging techniques.

Advantages and Limitations. Use of HF transmissions offers several advantages to the user.

1. The receivers and antennas are relatively simple and low cost.
2. Stable HF signals are available worldwide from approximately 20 countries (a detailed listing of HF transmitters is contained in AN 52-1.).
3. Groundwave signals (~ 160 km from the transmitter) can be received with about the same accuracy as transmitted.
4. Time pulse modulation and date information is available at these frequencies due to the availability of sufficient bandwidth.

However, several limitations also exist which may limit the use of HF in some applications.

1. HF skywave signals suffer erratic excursions in time delay from ionospheric irregularities; this degrades both time and frequency comparisons and causes unreliability of reception. Use of long term averaging techniques can remove some propagation anomalies thereby approaching precisions of parts-in-10^{10} but only over periods of 30 days or greater.
2. Propagation delays are difficult to determine to better than 1 ms because of ionospheric variability due to sunspots, time of day, seasons, distance, etc.
3. The number of hops propagated (transmission modes) is difficult to determine for paths exceeding 3500 km.

Time and Frequency Determination. For effective use of HF timing signals, it is important that certain precautions be observed to reduce the effects of the observable variations. For best results:

1. Schedule observation for an all-daytime or all-night-time transmission path between transmitter and receiver. Avoid twilight hours.
2. Choose the highest reception frequency which provides consistent reception.
3. Observe tick transmission for a few minutes to judge propagation conditions. The best measurements are made on days when signals show little jitter or fading. If erratic conditions seem to exist, indicated by considerable fading and jitter in tick timing, postpone the measurement. Ionospheric disturbances causing erratic reception sometimes last less than an hour, but may last several days.
4. Make time comparison measurements using the ticks with the earliest consistent arrival time (shortest distance mode).

One system for using HF signals is described in the following paragraphs.

TIME COMPARISON BY TICK PHASING ADJUSTMENT—Figure 4-1 shows a block diagram for a system to compare local time against time signals from an HF standard station such as WWV. The local frequency standard, an HP Model 105A/B Quartz Oscillator, drives an HP K09-59991A Clock. The K09-59991A derives a 1 PPS tick from the oscillator output, and it is these local ticks which trigger the oscilloscope sweep.

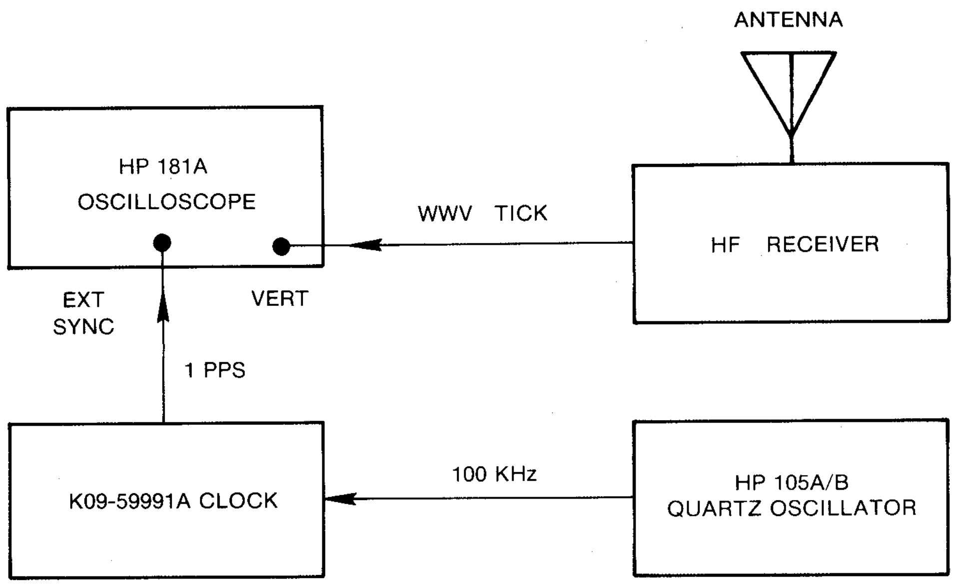

Figure 4-1. Time Comparison by Tick Phasing Adjustment

Upon initial observation, the local tick and the received tick, which is the master timing pulse, may be apart as much as a half second. With oscilloscope sweep time set at 1 sec or more, the WWV tick may be located with reference to the local tick. Adjustment of the Time Delay Thumbwheel switches on the K09-59991A delays the start of the oscilloscope sweep to bring the WWV tick toward the beginning of the oscilloscope trace. Successive adjustments of the Time Delay Thumbwheel and Oscilloscope sweep speed are made until the two ticks are brought to near coincidence (the Time Delay switch changes the phase of the K09-59991A tick without affecting oscillator frequency).

The WWV tick is a 5 ms pulse of a 1 kHz signal. It is this master timing pulse which is observed on the oscilloscope as the phasing of the local clock tick is shifted.

Once the two ticks have been brought into near coincidence, the calibrated Time Delay Switch gives the initial time reference between local time and the time of WWV. At this point the Time Delay Switch reading is logged. As the oscillator under test drifts with respect to the received time signals, the Time Delay Switch is readjusted to again establish near coincidence with the WWV tick. The amount of this readjustment (which indicates the time drift of the local oscillator) is again logged. These data, taken over a period of time and plotted, will enable accurate determination of drift rate and frequency error. Time comparisons made over several days can yield comparison accuracies of a few parts in 10^8 or better. Oscillator frequency can be readjusted to stay within the desired accuracy limits.

TICK AVERAGING—Since random variations in the propagation path cause variation in the arrival time of each WWV tick, the accuracy of time comparison measurements depends to a large extent on the operator's ability to judge tick arrival time. Excellent results can be obtained with the use of the variable persistence feature of the HP Model 141A or 181A Oscilloscopes. A 5 second persistence permits the operator to view repeated sweeps of WWV displayed together. From this display he can easily determine the time of earliest consistent tick arrival. An alternate method of tick averaging is to make an oscillogram using an HP Model 195A or 197A

Oscilloscope Camera or equivalent. Either method, variable persistence oscilloscope display or photographic time exposure, produces a record such as those shown in Figure 4-2. If oscilloscope sweep time has been calibrated accurately, a determination of the time comparison reading is possible.

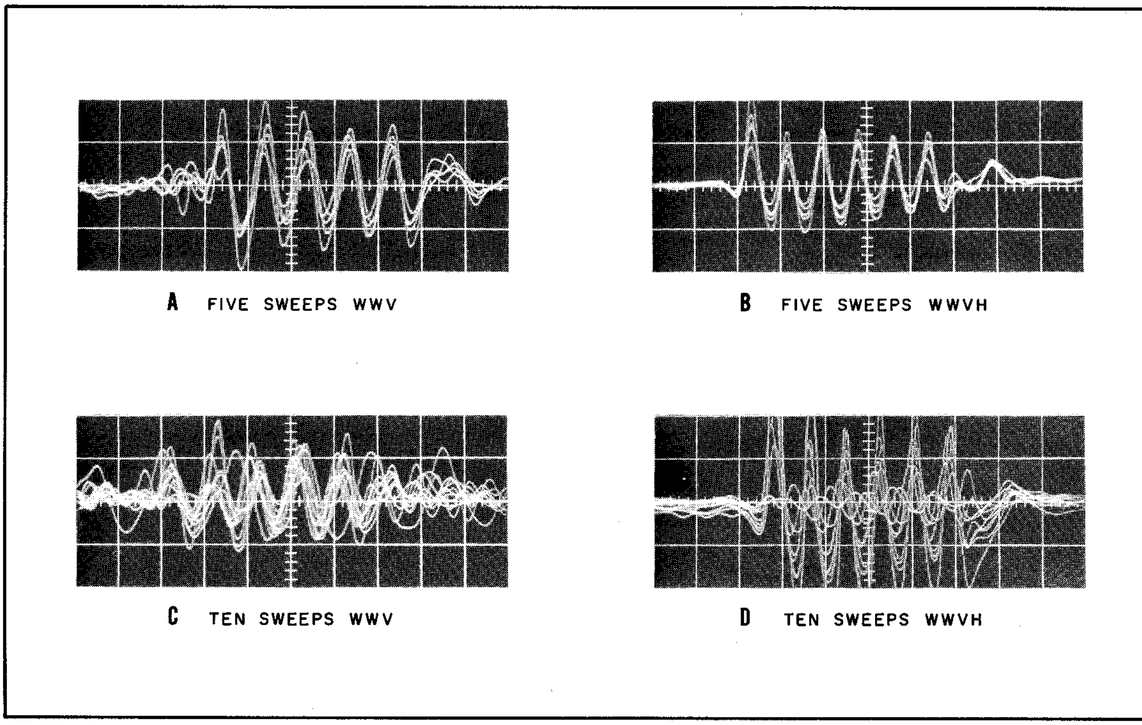

Figure 4-2. Photographic Tick Averaging

LOW FREQUENCY (LF) AND VERY LOW FREQUENCY (VLF) TRANSMISSIONS

Propagation of low frequency and very low frequency signals is discussed in AN 52-1. The phase stability and long range coverage of low frequency transmissions makes them particularly valuable for standard frequency broadcasts.

Variations in propagation conditions exist, and for accurate comparisons account must be taken of such variations as those associated with the diurnal shift (phase shifts occurring at sunrise and sunset). Factors affecting path phase velocity include ionospheric conditions and ground conductivity.

Since the phase velocity of long range VLF signals depends to an extent upon the effective height of the ionosphere, sudden ionosphere disturbances such as those occurring during solar flare events cause sudden phase anomalies. Other changes in VLF propagation are believed to relate to polar cap events, magnetic activity, nuclear explosions, and even to meteor showers.

Because relatively short periods serve for LF/VLF phase comparisons, diurnal phase shifts and other anomalies are not a serious problem, provided the user is aware of them.

Accuracy. A local frequency standard can be maintained to within a few parts in 10^{11} or better by comparison of its relative phase to that of a received LF or VLF carrier. Any one of a number of monitoring systems may be chosen to make this comparison possible, depending on the degree of precision required of the relative phase measurement. For the greatest precision, the local standard must have a low drift rate which is predictable to within a few parts in 10^{10} over several days.

If no better than a part in 10^8 is wanted, a nearly instantaneous direct comparison, for a short time, may be used. If a part in 10^9 is wanted, comparison must be continued long enough to reveal any ionospheric disturbance. Best results usually are obtained when the total propagation path is in sunlight and conditions are stable. Near sunrise and sunset there are noticeable shifts both in amplitude and in phase.

Advantages and Limitations. Major advantages to using LF or VLF time and frequency transmissions are:

1. Stable results are obtained within ranges to the transmitter of ~1600 km for LF and ~10000 km for VLF.
2. Single frequency comparisons can be made with relatively low cost equipment. Accuracies of parts in 10^{11} are possible over 24 hour periods most of the time.
3. Transmitters are usually stabilized with atomic standards and the transmissions are monitored by national laboratories which publish corrections that permit after-the-fact reference to their time scales.
4. Although LF and VLF signals are subject to diurnal effects, such phase changes are predictable and repeatable.
5. Time pulse modulation, which is possible with LF, permits time synchronization to ~100 μs or better provided the propagation delay is known.

Major limitations of LF and VLF transmissions are:

1. Ionospheric anomalies degrade reception in some geographical areas of the world referenced to an individual transmitter
2. LF and VLF propagations are subject to ionospheric variations; phase changes occur from diurnal effects, solar disturbances, nuclear blast effects, night-time irregularities, and long vs. short path interferences; strong attenuation over ice fields; and cycle slips.
3. Extreme care is required for optimum results. Proper interpretation of data requires experienced personnel.
4. It is impossible to initially set remote clocks to high accuracy via LF techniques alone.
5. Atmospheric noise at VLF is quite high and coherent signals often must be detected well below the noise. Noise from lightning strokes is maximum in this frequency band and the low attenuation rates of atmospheric noise at VLF allows worldwide propagation of such static.

Time and Frequency Determination. Determination of frequency is relatively simple for LF and VLF transmissions. A receiver, a phase-locked oscillator, a phase comparator and a strip chart recorder are all that is needed to make accurate measurements. A typical setup is shown in Figure 4-3.

Time, in comparison, is difficult to accurately transfer using LF and VLF transmissions due to the slow rise times of the time codes, if present. However, once synchronized, a clock can maintain synchronization indefinitely with the transmitter simply by phase tracking the LF/VLF broadcasts. In the case of WWVB, the transmitted signal is phase controlled to the UTC time scale and, hence, a user can phase-lock to UTC with only one initial time setting.

Several methods for using LF and VLF transmissions for time and frequency comparisons exist. The simplest of these methods is the single frequency comparison. The single frequency comparison technique is basically the same for either LF or VLF, however, the receiver for VLF must have a very narrow bandwidth (~0.01 to 0.001 Hz) in order to extract the VLF signal from the noise level in this frequency band. Let us now look at the single frequency technique for frequency comparison.